본 수업의 주 교재는 Silberschatz, Galvin, Gagne, "Operating System Concepts Essentials 2nd ed.", Wiley, 또는 한글번역본인 박민규, 조유근, "Operating System Concepts 에센셜 2판", 홍릉과학출판사입니다. 본 강의 동영상의 슬라이드는 이 책의 홈페이지에서 제공하는 것을 사용했음을 밝힙니다 (https://codex.cs.yale.edu/avi/os-book/OSE2/slide-dir/index.html). 다만 강의의 편의를 위해 내용 변경 없이 슬라이드 레이아웃을 변경하였고, 진도 관리에 필요한 경우 일부 슬라이드는 생략하였습니다.

Chapter 5: Process Synchronization

concept of process synchronization

critical-section problem

solutions of the critical-section problem

classical process-synchronization problems

Contents

- Background
- The Critical-Section Problem

Solution들

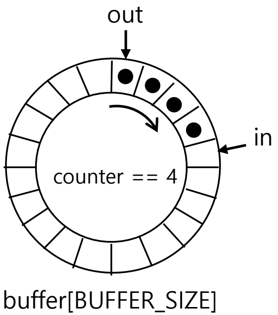
- Peterson’s Solution
- Synchronization Hardware
- Mutex Locks
- Semaphores
- Classic Problems of Synchronization
- Monitors

5.1 Background

- Processes can execute concurrently
  병행수행
- May be interrupted at any time, partially completing execution
- Concurrent access to shared data may result in data inconsistency
  → process synchronization 이 해결
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes

Producer-consumer problem

- Suppose that we wanted to provide a solution to the consumer-producer problem that fills all the buffers. → 병행실행시에 문제 발생. 할수 있음
- We can do so by having an integer counter that keeps track of the number of full buffers. Initially, counter is set to 0. It is incremented by the producer after it produces a new buffer and is decremented by the consumer after it consumes a buffer.




```
while (true) {    /* PRODUCER */
    /* produce an item in next produced */
    while (counter == BUFFER_SIZE) ;
        /* do nothing */
    buffer[in] = next_produced;
    in = (in + 1) % BUFFER_SIZE;
    counter++;
}
```

```
while (true) {     /* CONSUMER */
    while (counter == 0)
        ; /* do nothing */
    next_consumed = buffer[out];
    out = (out + 1) % BUFFER_SIZE;
    counter--;
    /* consume the item in next consumed */
}
```

Race Condition

- **counter++** could be implemented as

```
register1 = counter
register1 = register1 + 1
counter = register1
```

⇐ register에서의 동작.

- **counter--** could be implemented as

```
register2 = counter
register2 = register2 - 1
counter = register2
```

⇐ register에서의 동작.

```
register1 = counter
register1 = register1 + 1
counter = register1
register2 = counter
register2 = register2 - 1
counter = register2
```

OR

```
register2 = counter
register2 = register2 - 1
counter = register2
register1 = counter
register1 = register1 + 1
counter = register1
```

올바른 실행 순서.
⇒ 모든 동작이 마무리되고 나머지 동작이 실행.

- Consider this execution interleaving with "counter = 5" initially:
  - S0: producer execute `register1 = counter` {register1 = 5}
  - S1: producer execute `register1 = register1 + 1` {register1 = 6}
  - S2: consumer execute `register2 = counter` {register2 = 5}
  - S3: consumer execute `register2 = register2 - 1` {register2 = 4}
  - S4: producer execute `counter = register1` {counter = 6} ⇐ 원했던 결과는 5.
  - S5: consumer execute `counter = register2` {counter = 4}

⇒ Data의 consistency가 깨졌다.

5.2 Critical Section Problem

- Consider system of ***n*** processes {$p_0, p_1, \ldots p_{n-1}$}
- Each process has **critical section** segment of code 값을 증가하거나 감소하는 부분에 해당.
  - Process may be changing common variables, updating table, writing file, etc.
  - When one process in critical section, no other may be in its critical s ection
- ***Critical section problem*** is to design protocol to solve this
- Each process must ask permission to enter critical section in **e ntry section**, may follow critical section with **exit section**, the n **remainder section**

  = critical section에 해당x

Solution of Critical Section Problem

형식

- General structure of process P_i

```
do {
    entry section
        critical section
    exit section
        remainder section
} while (true);
```

- An example

⇒ 형식을제시하는것

```
do {
    while (turn == j);
```
특정조건 반복시 진입
```
        critical section
    turn = j;
        remainder section
} while (true);
```

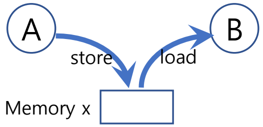
Solution to Critical-Section Problem

만족해야하는 조건

1. **Mutual Exclusion** - If process P_i is executing in its critical section, then no other processes can be executing in their critical sections
2. **Progress** - If no process is executing in its critical section and the re exist some processes that wish to enter their critical section, the n the selection of the processes that will enter the critical section next cannot be postponed indefinitely
3. **Bounded Waiting** - A bound must exist on the number of times that other processes are allowed to enter their critical sections afte r a process has made a request to enter its critical section and bef ore that request is granted

- Assume that each process executes at a nonzero speed
- No assumption concerning **relative speed** of the n processes

5.3 Peterson's Solution



- Good algorithmic description of solving the problem
- Two process solution (일반적인 경우는 n개에 대해 이야기) SW적인 해결책.
- Assume that the **load** and **store** machine-language instructions are atomic; that is, cannot be interrupted ⇒ 최소한의 HW의 조건.
- The two processes share two variables:
  - **int turn;** 0 아 1
  - **Boolean flag[2]** true, false
- The variable **turn** indicates whose turn it is to enter the critical sect ion
- The **flag** array is used to indicate if a process is ready to enter the critical section. **flag[i] = *true*** implies that process P_i is ready!

Algorithm for Process P_0 and P_1

```
/* P0 */
do {
        flag[0] = true; 의사표시
        turn = 1; 진입을 양보.
        while (flag[1] && turn == 1);
              critical section
        flag[0] = false;
              remainder section
  } while (true);
```

```
/* P1 */
do {
        flag[1] = true; //
        turn = 0;
        while (flag[0] && turn == 0);
              critical section
        flag[1] = false;
              remainder section
  } while (true);
```

Peterson's Solution (Cont.)

- Provable that the three CS requirement are met:

1. Mutual exclusion is preserved
   P_i enters CS only if:
   either **flag[j] = false** or **turn = i**
2. Progress requirement is satisfied
3. Bounded-waiting requirement is met

모두 조건을 만족한다.

```
/* P0 */
do {
    flag[0] = true;
    turn = 1;
    while (flag[1] && turn == 1);
        critical section
    flag[0] = false;
        remainder section
} while (true);
```

5.4 Synchronization Hardware

- Many systems provide hardware support for implementing the critical section code.
- Uniprocessors – could disable interrupts ⇒ 방해없이 실행가능.
  - Currently running code would execute without preemption
  - Generally too inefficient on multiprocessor systems
    - Operating systems using this not broadly scalable
- Modern machines provide special atomic hardware instructions
  - **Atomic** = non-interruptible
  - Either test memory word and set value
  - Or swap contents of two memory words 이들이 모두 atomic.

test_and_set Instruction

⇒ CPU 명령

```
boolean test_and_set (boolean *target)
 {
       boolean rv = *target;
       *target = TRUE;
       return rv;
 }
```

- Executed atomically

Solution using test_and_set

- Shared Boolean variable `lock`, initialized to `FALSE`

```
do {
      while (test_and_set(&lock))   false -> true.
          ; /* do nothing */
              /* critical section */
      lock = false;   다음프로세스가 critical에갈수있게함.
              /* remainder section */
   } while (true);
```

compare_and_swap Instruction

```
int compare_and_swap(int *value, int expected, int new_value)
{
        int temp = *value;

        if (*value == expected)
           *value = new_value;
    return temp;
}
```

- Executed atomically

Solution using compare_and_swap

- Shared integer `lock`, initialized to `0`;

```
do {
  while (compare_and_swap(&lock, 0, 1) != 0)
        ;
     /* critical section */
  lock = 0;
     /* remainder section */
} while (true);
```

0→1

Bounded-waiting Mutual Exclusion with test_and_set

이전은 기준 만족 X.

```
do {
   waiting[i] = true;
   key = true;            true → false로 변경되는 경우가 있다.
   while (waiting[i] && key)
      key = test_and_set(&lock);
   waiting[i] = false;
   /* critical section */
   j = (i + 1) % n;
   while ((j != i) && !waiting[j])
      j = (j + 1) % n;
   if (j == i)
      lock = false;
   else
      waiting[j] = false;   j를 critical에 오게하는 방법.
   /* remainder section */
} while (true);
```

```
boolean lock
boolean waiting[n];
```

5.5 Mutex Locks

- Previous solutions are complicated and generally inaccessible to a pplication programmers
- OS designers build software tools to solve critical section problem; Simplest is mutex lock
- Protect a critical section by first **`acquire()`** a lock then **`release()`** the lock
    - Boolean variable indicating if lock is available or not

unix의 mutexlock

- Calls to **`acquire()`** and **`release()`** must be atomic
    - Usually implemented via hardware atomic instructions
- But this solution requires **busy waiting**
    - This lock therefore called a **spinlock**

acquire() and release()

- ```
  acquire() {
       while (!available)
          ; /* busy wait */
       available = false;;
  }
  ```
- ```
  release() {
       available = true;
  }
  ```
- ```
  do {
      acquire lock
          critical section
      release lock
          remainder section
  } while (true);
  ```
  ```

5.6 Semaphore

- Synchronization tool that provides more sophisticated ways (than Mutex locks) for process to synchronize their activities. Unix 의 semaphore
- Semaphore *S* – integer variable
- Can only be accessed via two indivisible (atomic) operations
  - **wait()** and **signal()**
  - Originally called **P()** and **V()**
- Definition of the **wait()** operation

```
wait(S) {
    while (S <= 0)
        ; // busy wait
    S--;
}
```

- Definition of the **signal()** operation

```
signal(S) {
    S++;
}
```

Semaphore Usage

- **Counting semaphore** – integer value can range over an unrestricted domain
- **Binary semaphore** – integer value can range between 0 and 1
  - Same as a **mutex lock** 1 or 0
- Can solve various synchronization problems. Consider P1 and P2 that require S1 to happen before S2

```
Create a semaphore "synch" initialized to 0
P1:
    S1;
    signal(synch);
P2:
    wait(synch);
    S2;
```

Semaphore Implementation

= atomic함을 정의

- Must guarantee that no two processes can execute the **`wait()`** and **`signal()`** on the same semaphore at the same time
- Thus, the implementation becomes the critical section problem where the **`wait`** and **`signal`** code are placed in the critical section
  - Could now have **busy waiting** in critical section implementation
    = [illegible]
    - But implementation code is short
    - Little busy waiting if critical section rarely occupied
- Note that applications may spend lots of time in critical sections and therefore this is not a good solution

Semaphore Implementation with no Busy waiting

- With each semaphore there is an associated waiting queue

```
typedef struct{
  int value;
  struct process *list;
  } semaphore;
```

- Two operations:
  - **block** – place the process invoking the operation on the appropriate waiting queue
  - **wakeup** – remove one of processes in the waiting queue and place it in the ready queue

Implementation with no Busy waiting (Cont.)

```
wait(semaphore *S) {
    S->value--;
    if (S->value < 0) {
        add this process to S->list;
        block();
    }
}


signal(semaphore *S) {
    S->value++;
    if (S->value <= 0) {
        remove a process P from S->list;
        wakeup(P);
    }
}
```

Deadlock and Starvation

잘못사용하는경우

- **Deadlock** – two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes

=> 교착상태

- Let S and Q be two semaphores initialized to 1

P_0	P_1
`wait(S);`	`wait(Q);`
`wait(Q);`	`wait(S);`
`...`	`...`
`signal(S);`	`signal(Q);`
`signal(Q);`	`signal(S);`

- **Starvation** – **indefinite blocking**
  - A process may never be removed from the semaphore queue in which it is suspended
- **Priority Inversion** – Scheduling problem when lower-priority process holds a lock needed by higher-priority process
  - Solved via **priority-inheritance protocol**

우선순위 역전

5.7 Classical Problems of Synchronization

- Classical problems used to test newly-proposed synchronizati on schemes
  - Bounded-Buffer Problem
  - Readers and Writers Problem
  - Dining-Philosophers Problem

Bounded-Buffer Problem

- *n* buffers, each can hold one item
- Semaphore **`mutex`** initialized to the value 1 아 0
  => 접근제어
- Semaphore **`full`** initialized to the value 0
- Semaphore **`empty`** initialized to the value n

Bounded Buffer Problem (Cont.)

- Producer process

```
do {
      ...
    /* produce an item
       in next_produced */
    ...
  wait(empty);
  wait(mutex);
      ...
    /* add next produced
       to the buffer */
     ...
  signal(mutex);
  signal(full);
} while (true);
```

- Consumer process

```
do {
   wait(full);
   wait(mutex);
       ...
     /* remove an item from
        buffer to next_consumed */
       ...
   signal(mutex);
   signal(empty);
       ...
     /* consume the item
        in next consumed */
       ...
} while (true);
```

Readers-Writers Problem

- A data set is shared among a number of concurrent processes
  - Readers – only read the data set; they do ***not*** perform any updates
  - Writers – can both read and write
- Problem – allow multiple readers to read at the same time
  - Only one single writer can access the shared data at the same time

보내는 문제.

- Several variations of how readers and writers are considered – all involve some form of priorities
- Shared Data
  - Data set
  - Integer **`read_count`** initialized to 0
  - Semaphore **`rw_mutex`** initialized to 1 writer간 상호배제, first와 last reader와의 상호배제.
  - Semaphore **`mutex`** initialized to 1

read_count 의 갱신을 제어

Readers-Writers Problem (Cont.)

- Writer process

```
do {
    wait(rw_mutex);
       ...
    /* writing is performed */
       ...
   signal(rw_mutex);
} while (true);
```

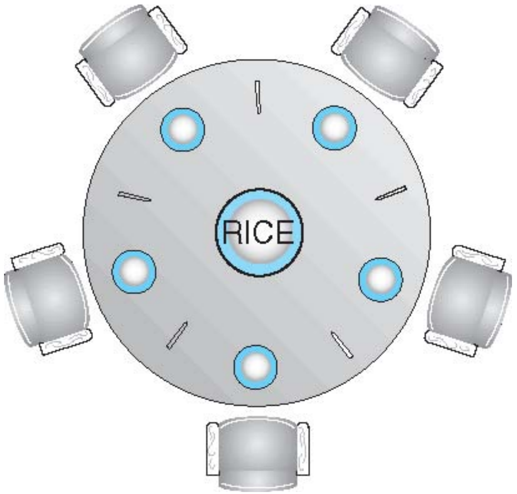
- Reader process

```
do {
       wait(mutex);
       read_count++;
       if (read_count == 1)
        wait(rw_mutex);
      signal(mutex);
         ...
       /* reading is performed */
         ...
      wait(mutex);
       read count--;
       if (read_count == 0)
      signal(rw_mutex);
      signal(mutex);
} while (true);
```

Dining-Philosophers Problem

동기화를 설명하기 위한 이야기

- Philosophers spend their lives alternating thinking and eating
- Don't interact with their neighbors, occasionally try to pick up 2 chopsticks (one at a time) to eat from bowl
  - Need both to eat, then release both when done
- In the case of 5 philosophers
  - Shared data
    - Bowl of rice (data set)
    - Semaphore chopstick [5] initialized to 1



Dining-Philosophers Problem Algorithm

- The structure of Philosopher *i*:

```
do {
     wait (chopstick[i] );
      wait (chopStick[ (i + 1) % 5] );

                 //  eat

      signal (chopstick[i] );
      signal (chopstick[ (i + 1) % 5] );

                  //  think

} while (TRUE);
```

- What is the problem with this algorithm?

Dead lock 이 가능

Dining-Philosophers Problem Algorithm (Cont.)

- Deadlock handling
  - Allow at most 4 philosophers to be sitting simultaneously at the ta ble.
  - Allow a philosopher to pick up the forks only if both are available (picking must be done in a critical section.
  - Use an asymmetric solution -- an odd-numbered philosopher pick s up first the left chopstick and then the right chopstick. Even-num bered philosopher picks up first the right chopstick and then the le ft chopstick.

5.8 Monitors

동기화를 위한 추상화 방법.

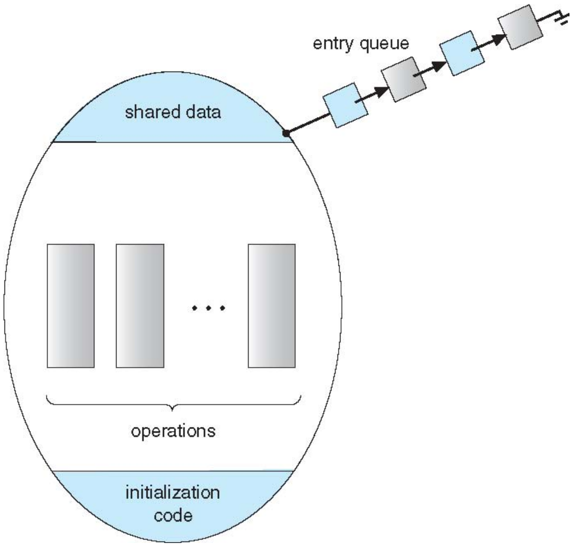
- A high-level abstraction that provides a convenient and effective mechanism for process synchronization
- *Abstract data type*, internal variables only accessible by code within the procedure

```
monitor monitor-name
{
  // shared variable declarations
  procedure P1 (…) { …. }

  procedure Pn (…) {……}

     Initialization code (…) { … }
}
```

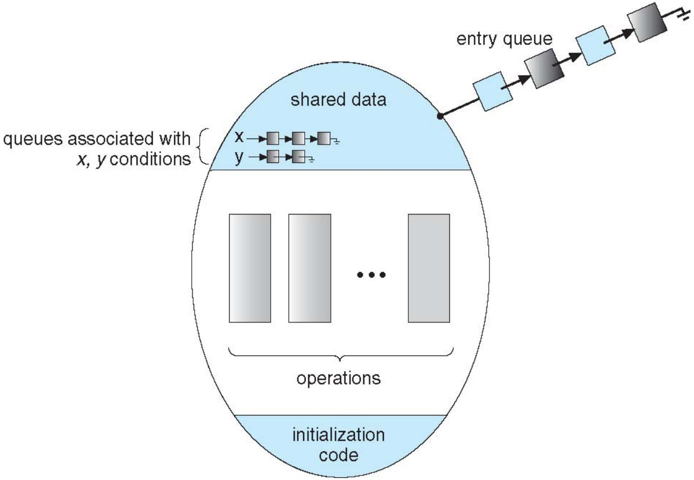
- Only one process may be active within the monitor at a time
- But not powerful enough to model some synchronization schemes



Condition Variables

모니터가 지원하지 않는 정교한 condition을 제공.

- **`condition x, y;`**
- Two operations are allowed on a condition variable:
  - **`x.wait()`** – a process that invokes the operation is suspended until **`x.signal()`**
  - **`x.signal()`** – resumes one of processes (if any) that invoked **`x.wait()`**
    - If no **`x.wait()`** on the variable, then it has no effect on the variable



5.11 The Deadlock Problem

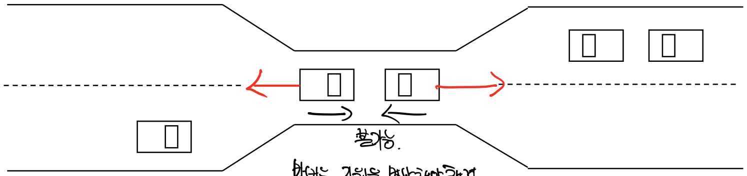
- A set of blocked processes each holding a resource and waiting to acquire a resource held by another process in the set

- Example
  - System has 2 disk drives
  - P_1 and P_2 each hold one disk drive and each needs another one

- Example: semaphores A and B, initialized to 1

P_1		P_2
wait (A);		wait(B)
wait (B);	– 둘다실패 –	wait(A)

Bridge Crossing Example



불가능.

한쪽은 자원을 반납해야 해결

- Traffic only in one direction
- Each section of a bridge can be viewed as a resource
- If a deadlock occurs, it can be resolved if one car backs up (preempt resources and rollback)
- Several cars may have to be backed up if a deadlock occurs
- Starvation is possible

매번 같은 프로세스가 자원을 희생하면?

Deadlock Example

```
/* thread one runs in this function */

void *do_work_one(void *param)
{

   pthread_mutex_lock(&first_mutex);

   pthread_mutex_lock(&second_mutex);

   /** * Do some work */
   pthread_mutex_unlock(&second_mutex);

   pthread_mutex_unlock(&first_mutex);

   pthread_exit(0);

}
```

```
/* thread two runs in this function */

void *do_work_two(void *param)
{

   pthread_mutex_lock(&second_mutex);

   pthread_mutex_lock(&first_mutex);

   /** * Do some work */
   pthread_mutex_unlock(&first_mutex);

   pthread_mutex_unlock(&second_mutex);

   pthread_exit(0);

}
```

Deadlock Characterization

4가지의 필요조건.

Deadlock can arise if four conditions hold simultaneously.

- **Mutual exclusion**: only one process at a time can use a resource
- **Hold and wait**: a process holding at least one resource is waiting to acquire additional resources held by other processes
- **No preemption**: a resource can be released only voluntarily by th e process holding it, after that process has completed its task
- **Circular wait**: there exists a set $\{P_0, P_1, \ldots, P_n\}$ of waiting processes such that P_0 is waiting for a resource that is held by P_1, P_1 is waitin g for a resource that is held by P_2, …, P_{n-1} is waiting for a resource that is held by P_n, and P_n is waiting for a resource that is held by P0.

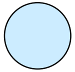
Resource-Allocation Graph

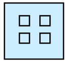
자원할당 그래프

A set of vertices *V* and a set of edges *E*.

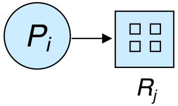
- V is partitioned into two types:
  - $P = \{P_1, P_2, \ldots, P_n\}$, the set consisting of all the processes in the system
  - $R = \{R_1, R_2, \ldots, R_m\}$, the set consisting of all resource types in the system
- **request edge** – directed edge $P_i \rightarrow R_j$
- **assignment edge** – directed edge $R_j \rightarrow P_i$

Resource-Allocation Graph (Cont.)

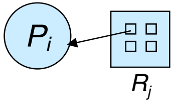
- Process 

- Resource Type with 4 instances 

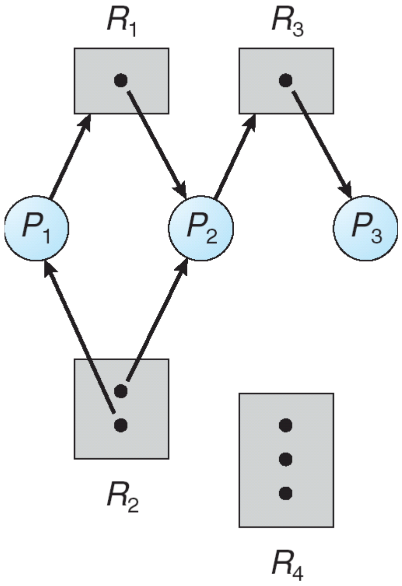
- P_i requests instance of R_j



- P_i is holding an instance of R_j

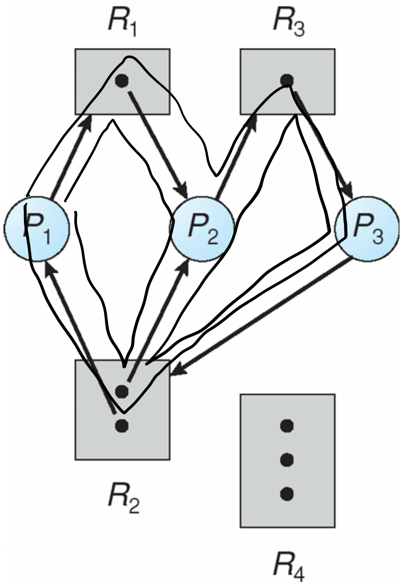


Example of a Resource Allocation Graph

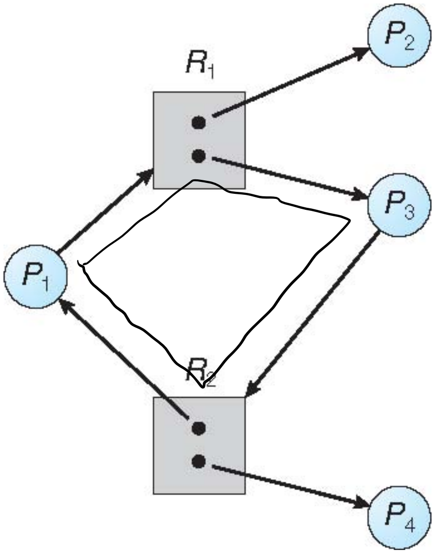


Resource Allocation Graph With A Deadlock

=> 그래프상 cycle이 존재



Graph With A Cycle But No Deadlock



Cycle이 해제될 가능성이 있다.

Basic Facts

- If graph contains no cycles $\Rightarrow$ no deadlock
- If graph contains a cycle $\Rightarrow$
  - if only one instance per resource type, then deadlock
  - if several instances per resource type, possibility of deadlock

Methods for Handling Deadlocks

- Ensure that the system will never enter a deadlock state:
  - Deadlock prevention
  - Deadlock avoidance
- Allow the system to enter a deadlock state and then recover
- Ignore the problem and pretend that deadlocks never occur i n the system; used by most operating systems, including UNI X